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APPROXIMATIONS FOR NEUTRON EMISSION SPECTRA FROM PROTON COLLISIONS BETWEEN 20 AND 500 MeV ON NUCLEI OF A $\geq$ 12

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16. ABSTRACT

When high-energy protons from solar proton events or trapped radiation belts impinge on spacecraft structures, secondary particles are emitted. The most pernicious secondaries, from either a biological or physical standpoint, are the cascade and evaporation neutrons because of their reaction with matter leading to radioactive materials in the spacecraft structures. This report presents an empirically determined cascade and evaporation neutron emission spectra for protons of energy between 20 and 500 MeV incident on all materials at or above carbon in mass number.

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APPROXIMATIONS FOR NEUTRON EMISSION SPECTRA FROM PROTON COLLISIONS BETWEEN 20 AND 500 MeV ON NUCLEI OF A $\geqslant$ 12

INTRODUCTION

The approximations given in this report are based on the intranuclear-cascade data generated by H.W. Bertini of Oak Ridge National Laboratory (ORNL) [1]. R.G. Alsmiller, Jr., and associates have made detailed fits of this data as described in References 2 and 3. The present effort was undertaken for those space shielding applications where the neutron spectrum may be chosen less accurately but may be more easily integrated into a larger computer transport code with access to a limited computer memory. In addition, the present fits are more satisfying because the number of coefficients for the data has been reduced by a factor of more than 30 over those of Reference 2, while also providing an analytical expression of the neutron emission spectra as a function of neutron energy, proton energy, and target A number. In Reference 3, Alsmiller required an elaborate double interpolation formula between ten elements and nine energies in order to find a neutron energy spectra formula for a given proton energy and target, whereas the approximate analytical expression given here completely defines the neutron spectra for any given proton energy and target in the range of validity.

Of course, one should suspect that if the number of coefficients is reduced by a factor of 30, then the accuracy of the fits might vary accordingly. However, this was not the case. The difference between Alsmiller's fits and the present work over a neutron spectrum was usually quite small, with a few bad exceptions, notably evaporation neutrons from carbon and oxygen. The agreement is better than was observed between the Bertini intranuclear cascade calculations and experiment. In order for the reader to evaluate the accuracy of the present work, as compared to Alsmiller [2,3], graphs are given at the end of this report for all energies and target nuclei generated by Bertini and given in References 2 and 3.

USE OF CURRENT FITS

This report provides analytical fits for two specific neutron source groups. The first group is the proton-induced evaporation neutrons which are integrated over all directions (0 to 180 deg). By dividing the analytically fit neutron energy spectrum by 4π, one can derive a very reasonable estimate of the true isotropic emission spectra in units of neutrons/(MeV-steradian). The second group of neutron spectra is the proton-induced cascade neutrons which are also integrated over all directions (0 to 180 deg). However, since cascade neutrons are fairly directional, one must use judgment in

deriving a reasonable angular emission spectra from the given fits. If one needs an accurate angular emission spectra, then Alsmiller's [2,3] data are recommended since he has given fits for four angular intervals (0 to 30 deg, 30 to 60 deg, 60 to 90 deg, 90 to 180 deg). However, many good approximations for thin shields can be made using the (0 to 180 deg) fits given here, if one can assume a straight-ahead approximation (i.e., assume all cascade neutrons are emitted in the same direction as the incident proton). This should provide a conservative estimate for normal incident protons on a slab or isotropic incident protons on the surface of a spherical shell with detectors at the center of the sphere.

No detailed attempt will be made to explain how the data should be used except for the following example for neutron flux estimation:

$$\phi(E_N, x) = \int_{E_p} \sum_{in} (E_p, A)\, \phi_x(E_p)\, F(E_N | E_p, A, Z)\, dE_p = \frac{\text{neutrons}}{\text{gm-MeV}} \quad , (1)$$

where

$\phi(E_N, x)$ = neutron emission energy spectrum created at depth x (gm/cm²) ,

$\sum_{in} (E_p, A)$ = inelastic cross section for proton (of energy E_p on elements of mass number A) in units of cm²/gm,

$$\cong \frac{2.4 \times 10^{-2}}{A^{0.27}} \quad (\text{cm}^2/\text{gm}),$$

$\phi_x (E_p)$ = proton spectra at depth x(gm/cm²) in units of proton/(cm² - MeV)

and

$F(E_N | E_p, A, Z)$ = neutron emission spectra function fit in units of neutrons/MeV for a proton of energy E_p having an inelastic collision on a target defined by mass number A and atomic number Z.

Observing the function $\phi(E_N,x)$ in equation (1), one sees that to find the neutron energy spectrum at depth X^*, the function must be integrated over x for all values from 0 to X^*; thus, for thin shields

$$\Phi_{X^*}(E_N) = \int_0^{X^*} \phi(E_N, x)\, T(E_N, X^* - x)\, dx = \frac{\text{neutrons}}{\text{cm}^2\text{-MeV}} \qquad (2)$$

where $T(E_N, X^* - x)$ is a dimensionless transport kernel for the attenuation of neutron flux from x to X^*. When X^* is sufficiently large (perhaps a mean free path), a neutron transport code should be used. For space vehicle shielding, it is worth noting that a 1-MeV neutron has a mean free path in aluminum of about 15 gm/cm², a 20-MeV neutron has a mean free path of about 25 gm/cm², and a 100-MeV neutron has a mean free path of about 45 gm/cm². If the shield contains hydrogen, the value of X^* should be fairly small, perhaps less than 0.5 mean free path. Methods for performing the integration of equation (2), and especially the choice of a transport kernel will be left to the reader.

ANALYTICAL APPROXIMATIONS FOR NEUTRON EMISSION SPECTRA

The following pages give the neutron emission spectra for an incident proton of energy E_p on targets of $A \geqslant 12$. Table 1 gives the derived cascade neutron spectra formula for the angular interval of 0 to 180 deg. However, most of the cascade neutrons are emitted in the forward direction (0 to 60 deg) as measured from the proton direction.

Table 2 gives the derived evaporation neutron spectra formula for the angular interval of 0 to 180 deg. Here it can be assumed that the neutrons are emitted isotropically from the excited nucleus.

The original data generated by Bertini [1] and fit by Alsmiller, et al. [2,3], consisted of ten target nuclei and nine incident proton energies from 25 to 400 MeV. Since this report attempts to simplify the original ORNL curve fits, it seems appropriate to show a comparison of our results for each energy and target element that was originally fit by Alsmiller, even though the number was extremely large (90). Also, many of the neutron spectra shown here are not depicted in other reports, even though ORNL has extensively published most of their results.

Figures 1 through 10 depict the cascade neutron spectra for ten target nuclei with the nine proton energies shown per figure. It should be noted that the spectral data are

TABLE 1. CASCADE NEUTRON ENERGY SPECTRUM FOR PROTONS INCIDENT ON NUCLEI OF $A \geqslant 12$

$$F(E_N|E_p, A, Z) = [B_1 + B_2(A\text{-}Z) + B_3(A\text{-}Z)^2] \exp(B_4 t + B_5 t^2 + B_6 t^3); \quad [\frac{\text{Neut.}}{\text{MeV}}]$$

where

$$t = \frac{E_N - \epsilon}{E_p - \epsilon} \quad ; \quad \epsilon \leqslant E_N \leqslant E_p \quad ; \quad 20 \leqslant E_p \leqslant 500 \text{ MeV} \quad ,$$

$$\epsilon = -3.018(-1) + 4.265(-1) \frac{Z}{A^{1/3}} + 5.591(-3) \frac{Z^2}{A^{2/3}} \quad * \quad ,$$

ϵ = minimum neutron energy,

E_N = cascade neutron energy = $\epsilon + t(E_p - \epsilon)$; $0 \leqslant t \leqslant 1$,

E_p = incident proton energy,

A,Z = mass number and atomic number of target nuclei,

$$B_1 = +5.763(-2) - 1.795(-4)E_p + 2.194(-7)E_p^2 \quad ,$$

$$B_2 = -9.499(-4) + 1.805(-5)E_p + 9.225(-8)E_p^2 + 2.582(-10)E_p^3 - 2.986(-13)E_p^4 \quad ,$$

$$B_3 = 4.513(-6) - 1.0603(-7)E_p + 6.406(-10)E_p^2 - 2.022(-12)E_p^3 + 2.481(-15)E_p^4 \quad ,$$

$$B_4 = -2.272 - 1.2283(-1)E_p + 5.288(-4)E_p^2 - 1.1356(-6)E_p^3 + 9.691(-10)E_p^4 \quad ,$$

$$B_5 = +7.845 + 1.040(-1)E_p - 2.260(-4)E_p^2 + 1.1429(-7)E_p^3 \quad , \text{ and}$$

$$B_6 = -8.007 - 6.950(-3)E_p - 7.495(-5)E_p^2 + 2.0826(-7)E_p^3 \ .$$

* a.bc(Y) = a.bc x 10^Y

TABLE 2. EVAPORATION NEUTRON ENERGY SPECTRUM FOR PROTONS INCIDENT ON NUCLEI OF $A \geq 12$

$$G(E_N|E_p, A, Z) = C_{1i} \exp\left[C_{2i}\left(\frac{E_N}{\Delta}\right) + C_{3i}\left(\frac{E_N}{\Delta}\right)^2\right] \quad ; \quad \left[\frac{\text{Neut.}}{\text{MeV}}\right]$$

where

$$\Delta = \frac{E_p}{C_{4i} + C_{5i}E_p} \quad ; \quad 0 \leq E_N \leq \Delta \quad ; \quad 20 \leq E_p \leq 500\,\text{MeV} \quad ; \quad i = 1, 2 .$$

E_N = evaporation neutron energy,

E_p = incident proton energy,

Δ = maximum neutron energy,

A,Z = mass number and atomic number of target nuclei.

When $i = 1$ $\quad A \geq 65$

$$C_{11} = +2.46 \times 10^{-1} + 5.5 \times 10^{-3}\,(A\text{-}Z) + 5.2 \times 10^{-5}\,(A\text{-}Z)^2$$

$$C_{21} = -1.87 + 1.12 \times 10^{-2}\,A$$

$$C_{31} = +5.305 \times 10^{-1} - 9.646 \times 10^{-1}\,(A\text{-}Z)^{1/3}$$

$$C_{41} = +1.92 + 3.0 \times 10^{-2}\,(A\text{-}Z)$$

$$C_{51} = +3.2766 \times 10^{-2} + 9.874 \times 10^{-3}\,(A\text{-}Z)^{1/3}$$

When $i = 2$ $\quad 12 \leq A < 65$

$$C_{12} = +7.0 \times 10^{-3}\,(A\text{-}Z) + 1.8 \times 10^{-4}\,(A\text{-}Z)^2$$

$$C_{22} = -7.3594 + 1.882\,(A\text{-}Z)^{1/3}$$

$$C_{32} = +6.479 - 3.774\,(A\text{-}Z)^{1/4}$$

$$C_{42} = \frac{A^2}{93.0 + 0.316A^2}$$

$$C_{52} = 4.39 \times 10^{-2} + 3.40 \times 10^{-4}\,A$$

plotted as a function of t in the interval of 0 to 1. This permits a simple comparison of all data on the same scale. The t scale is converted to the E_N scale by the relationship $E_N = \epsilon + t\,(E_p - \epsilon)$, where the variables are defined in Table 1.

Figures 11 through 19 present the evaporation neutron spectra plotted as a function of the neutron energy. Each of the nine figures is for a single incident proton energy (25 MeV-400 MeV) on each of eight target elements from oxygen through lead.

Figures 20 through 22 show the evaporation neutron spectra for protons on carbon and uranium for the nine incident proton energies. The evaporation neutron spectra for 25-MeV protons on carbon (Fig. 20) was the poorest fit of all sets. The second poorest is 25-MeV protons on oxygen (Fig. 11).

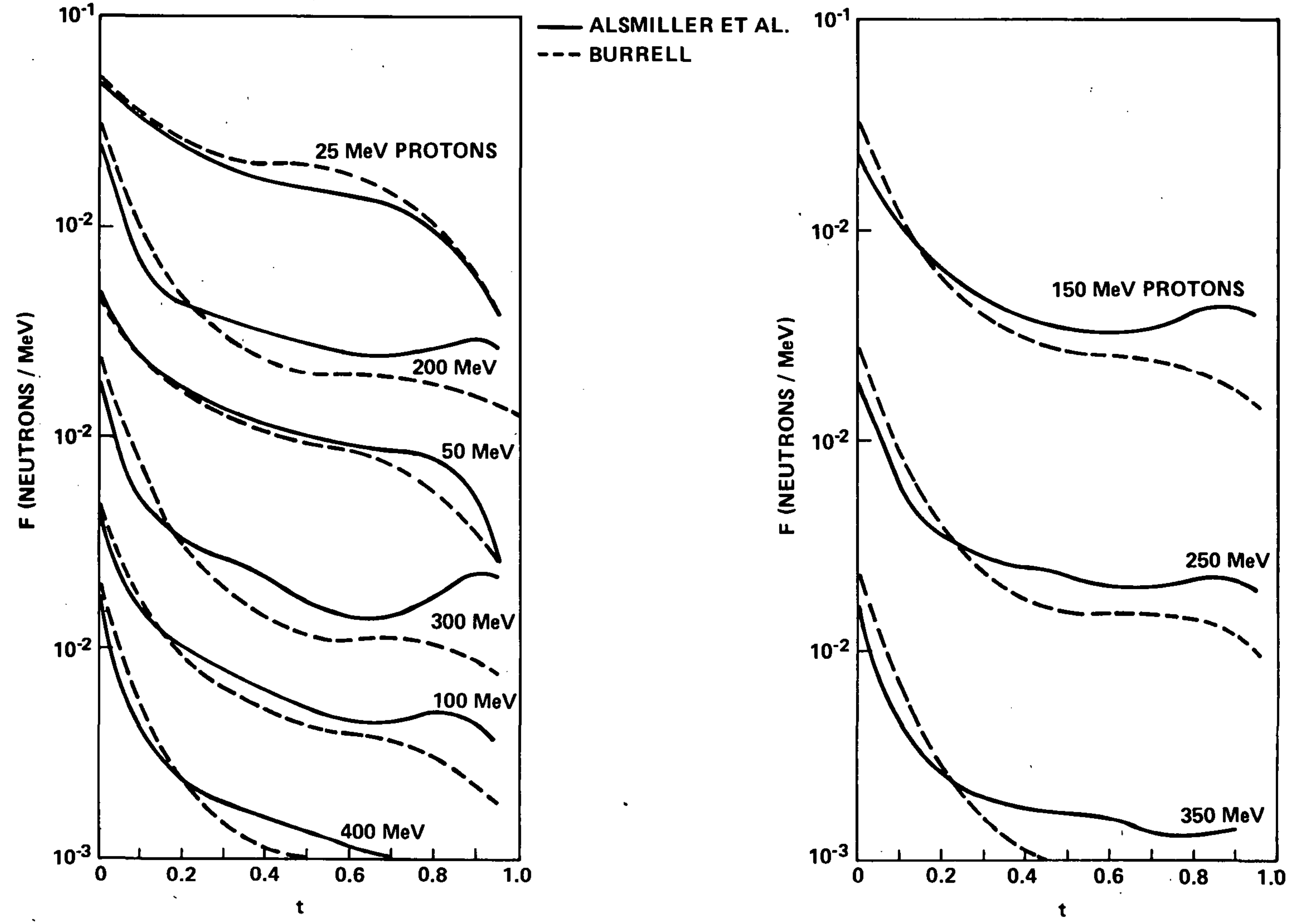

Figure 1. Cascade neutron spectra from carbon, A = 12, Z = 6.

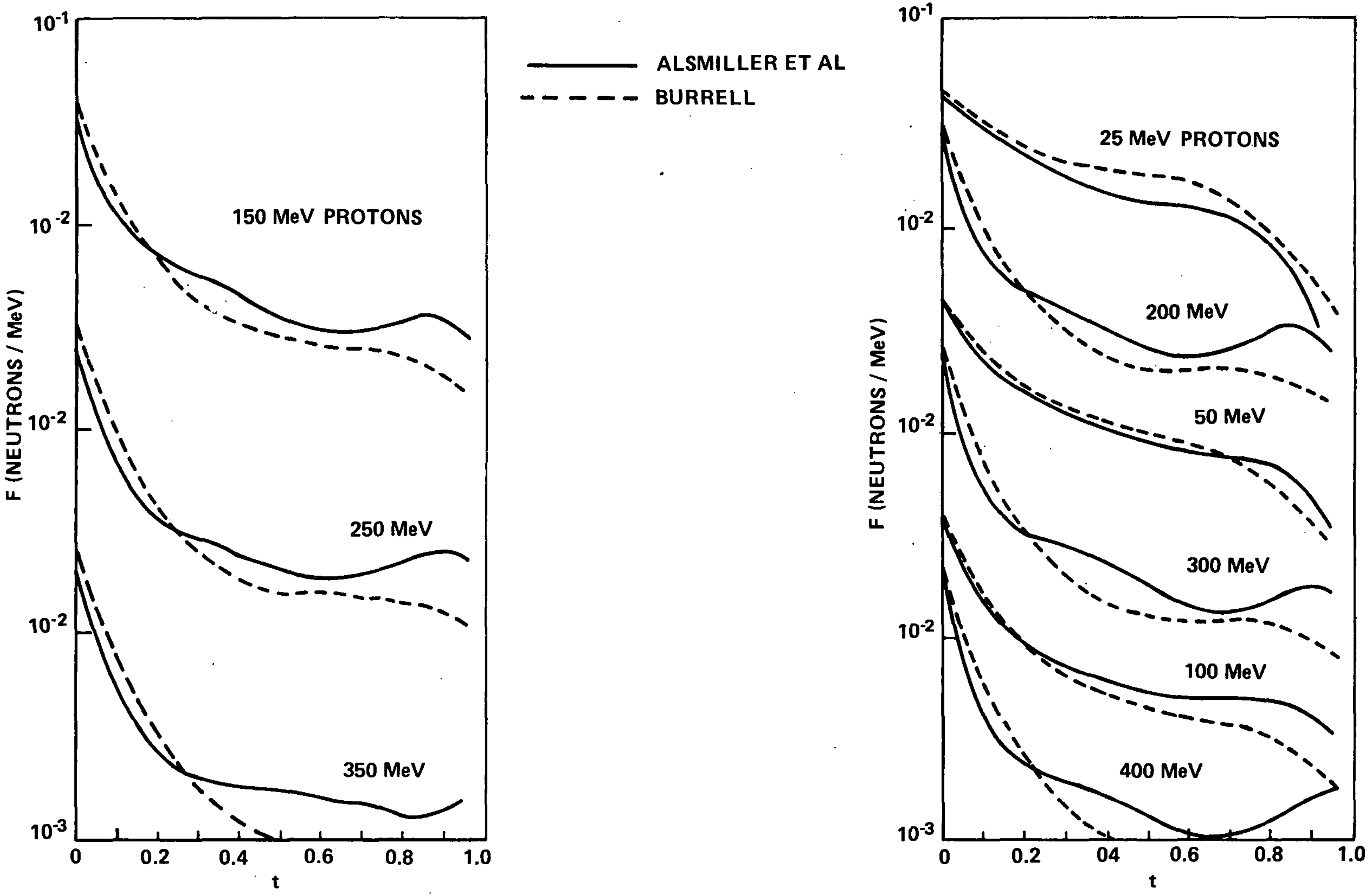

Figure 2. Cascade neutron spectra from oxygen, A = 16, Z = 8.

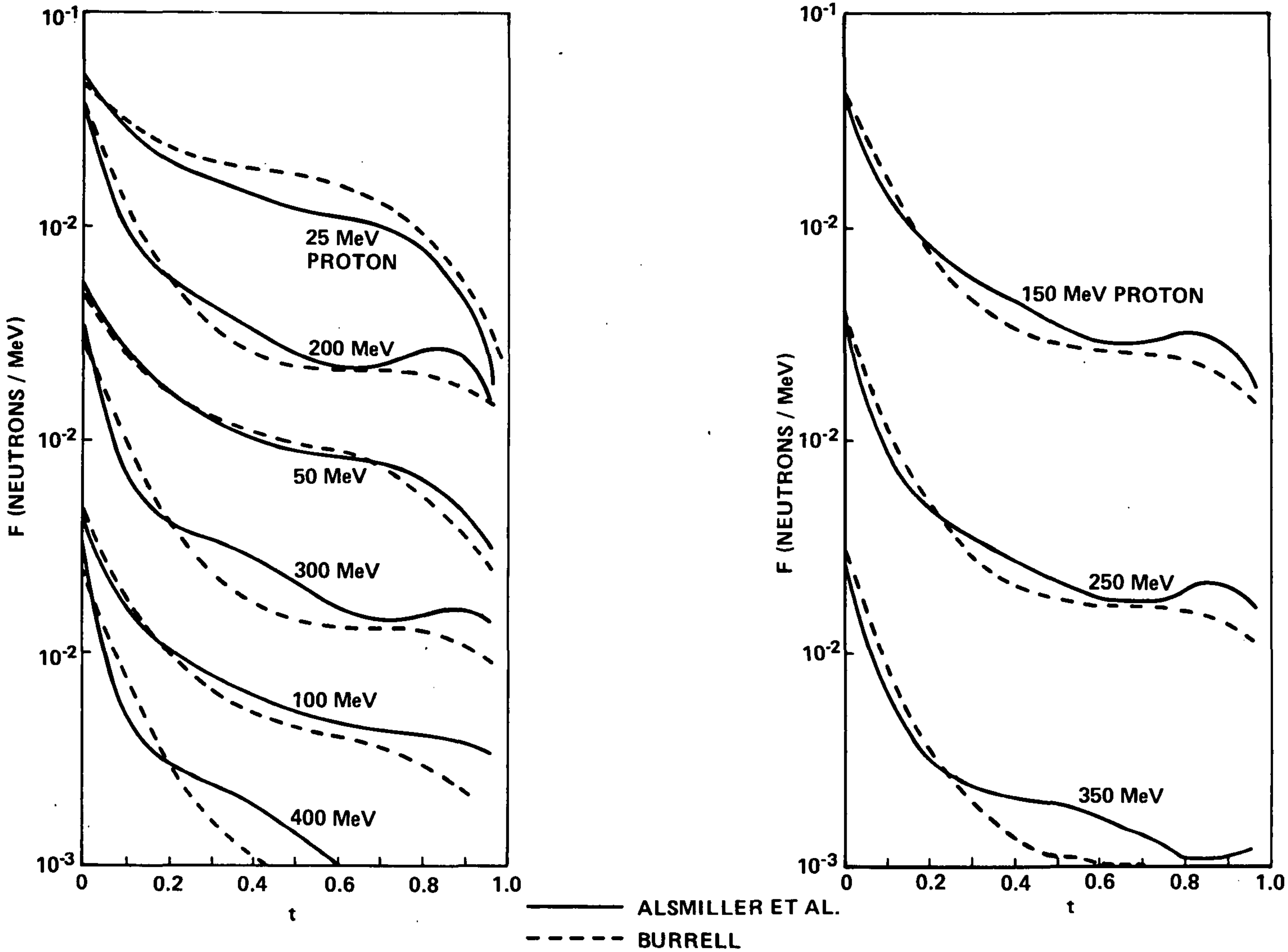

Figure 3. Cascade neutron spectra from aluminum, A = 27, Z = 13.

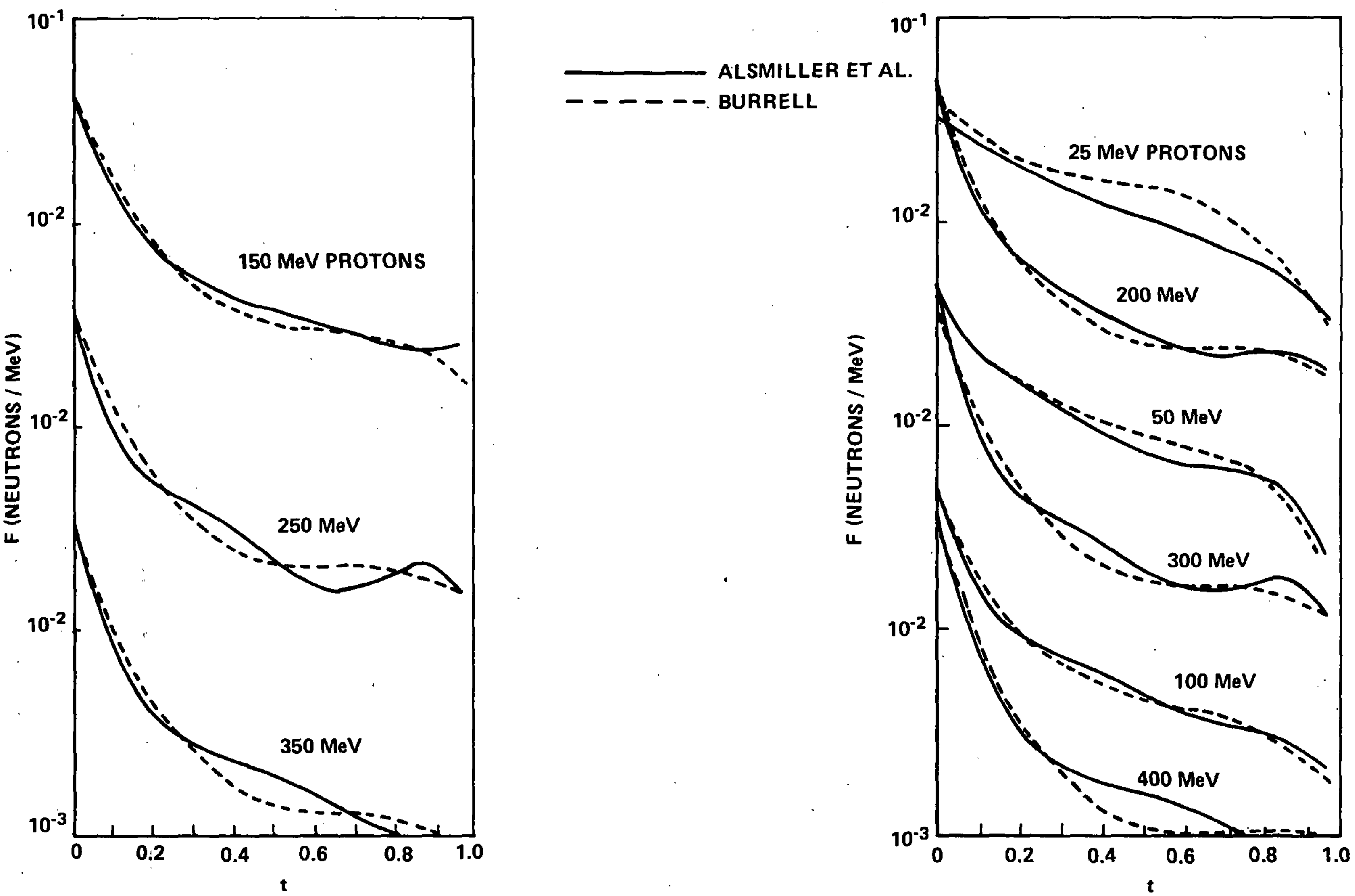

Figure 4. Cascade neutron spectra from chromium, A = 52, Z = 24.

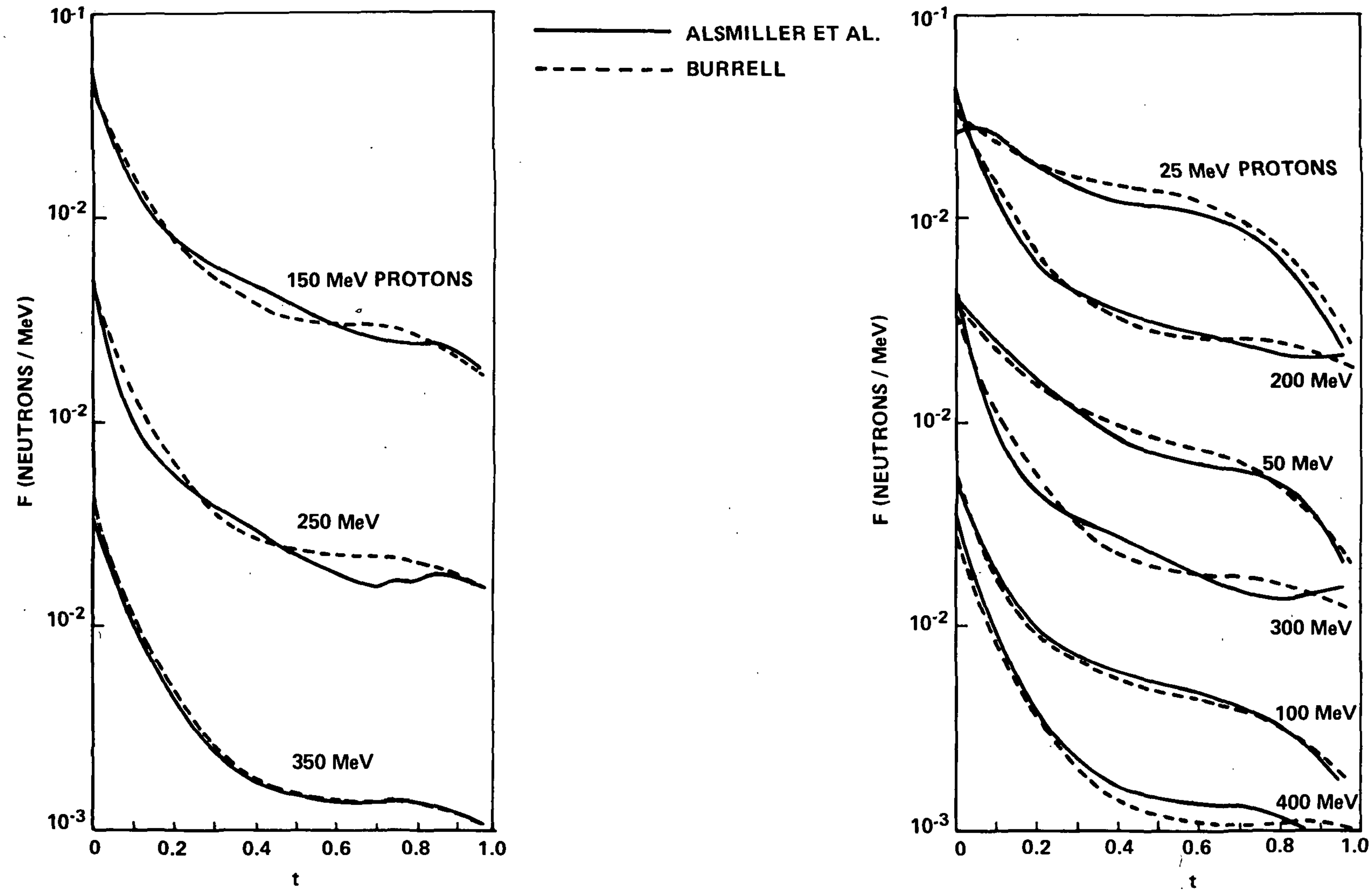

Figure 5. Cascade neutron spectra from copper, A = 65, Z = 29.

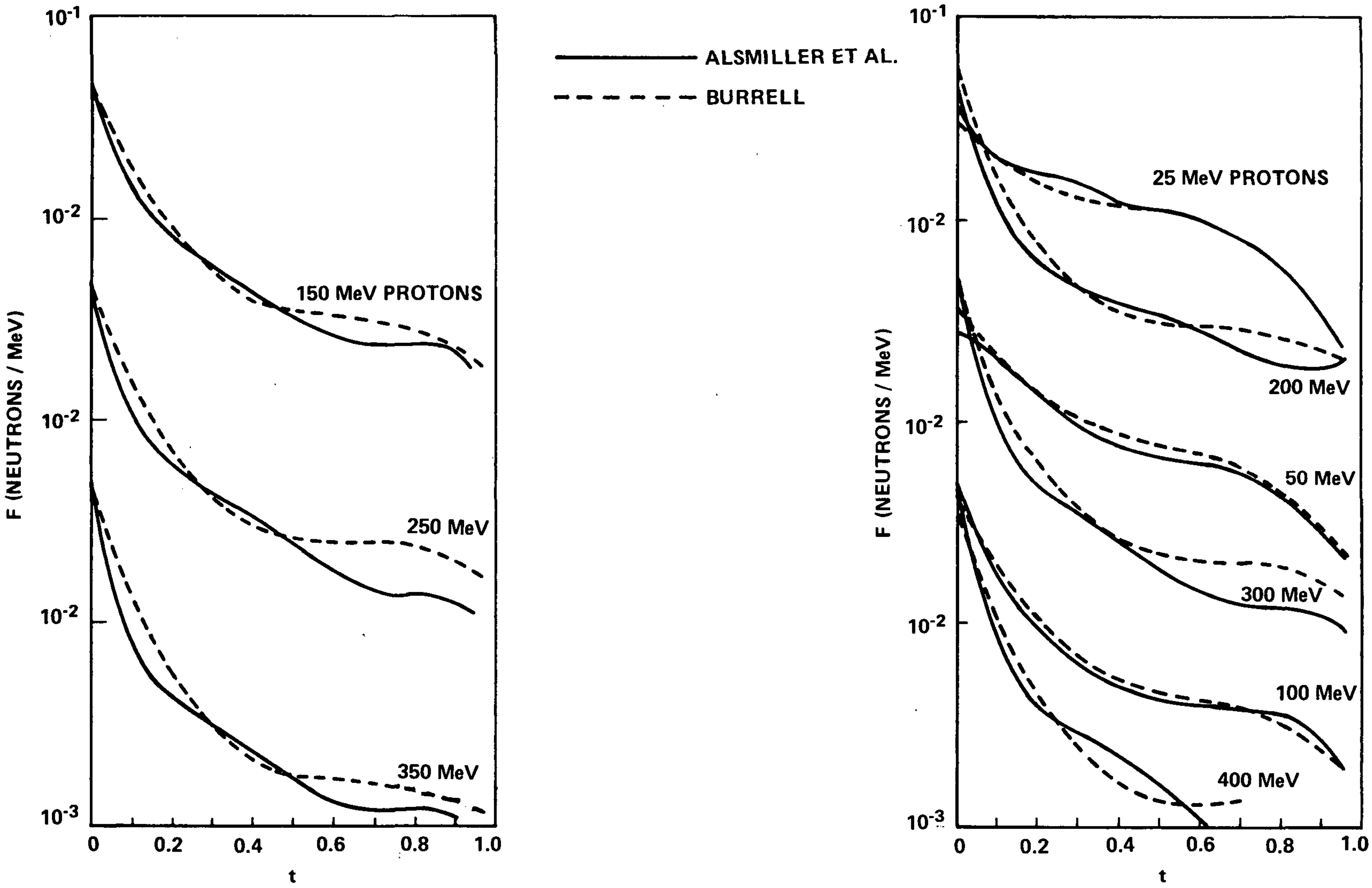

Figure 6. Cascade neutron spectra from ruthenium, A = 100, Z = 44.

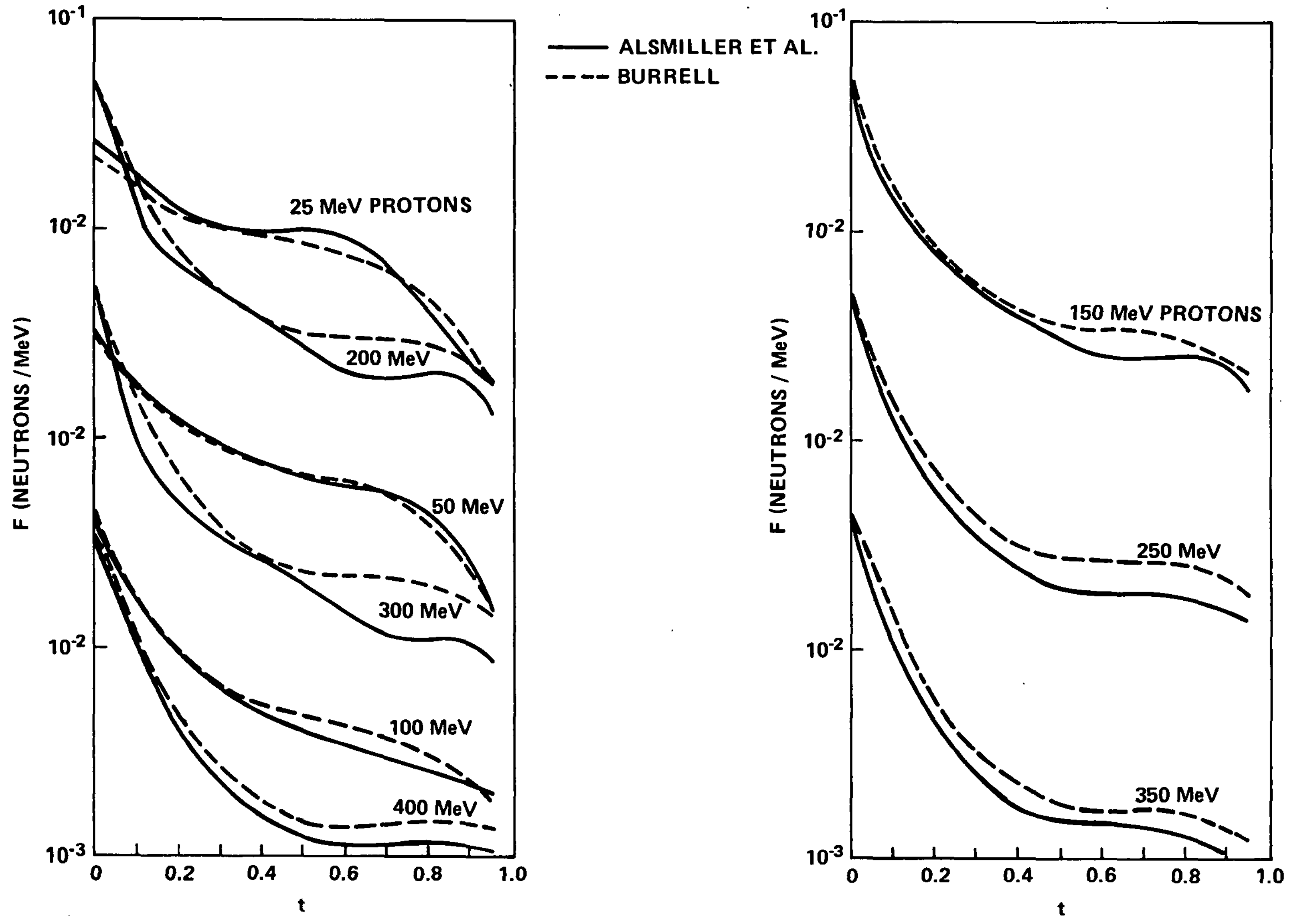

Figure 7. Cascade neutron spectra from cerium, A = 140, Z = 58.

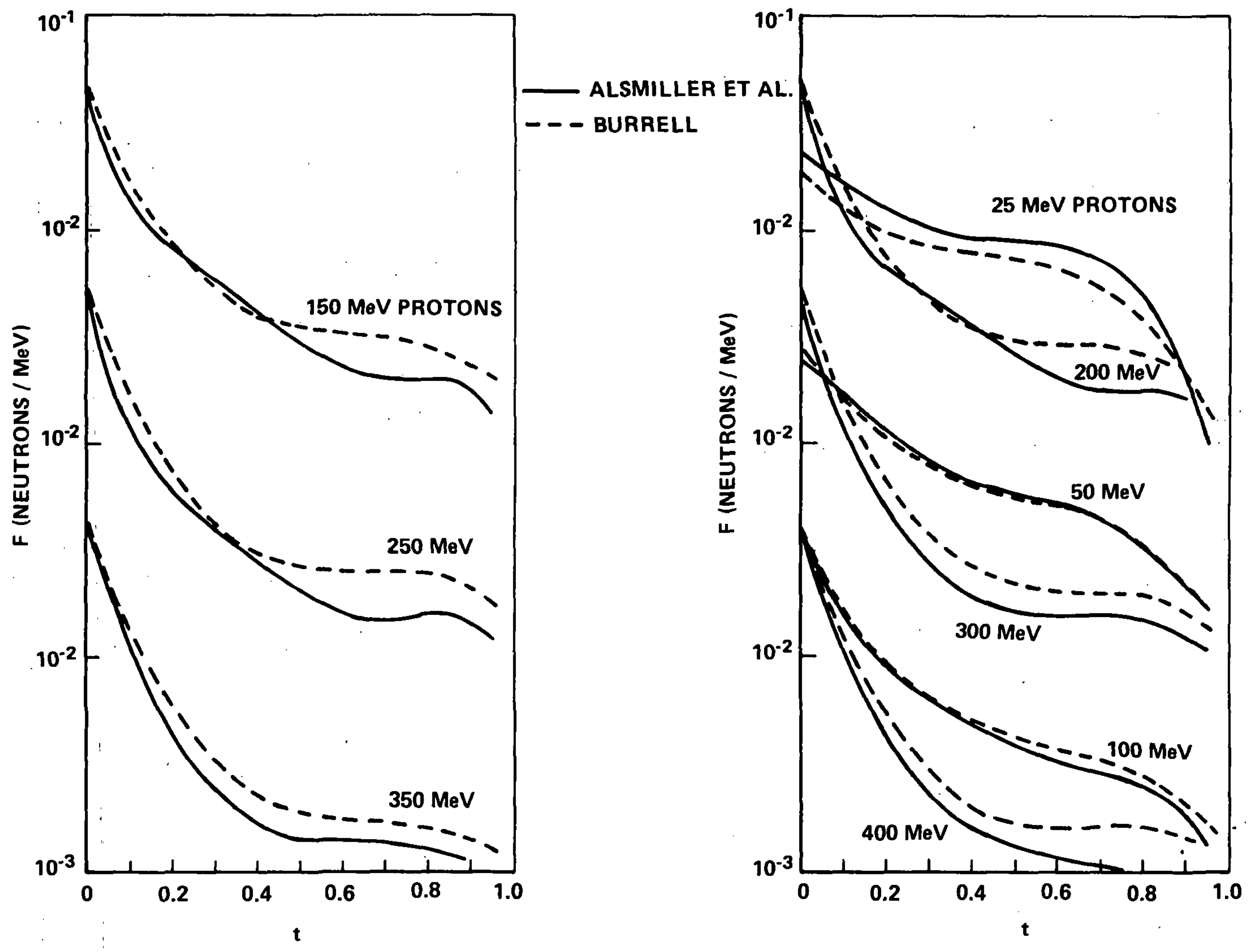

Figure 8. Cascade neutron spectra from tungsten, A = 184, Z = 74.

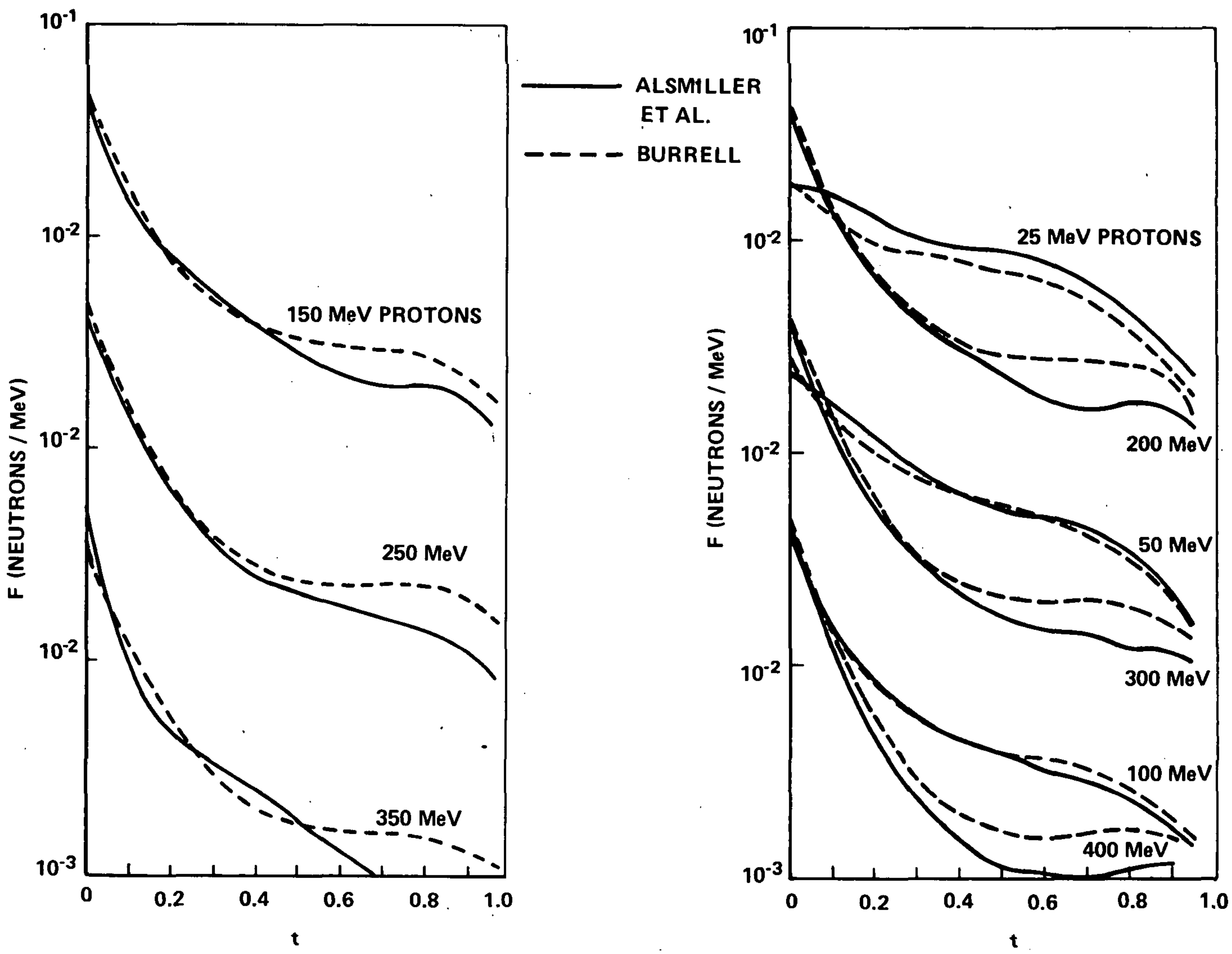

Figure 9. Cascade neutron spectra from lead, A = 207, Z = 82.

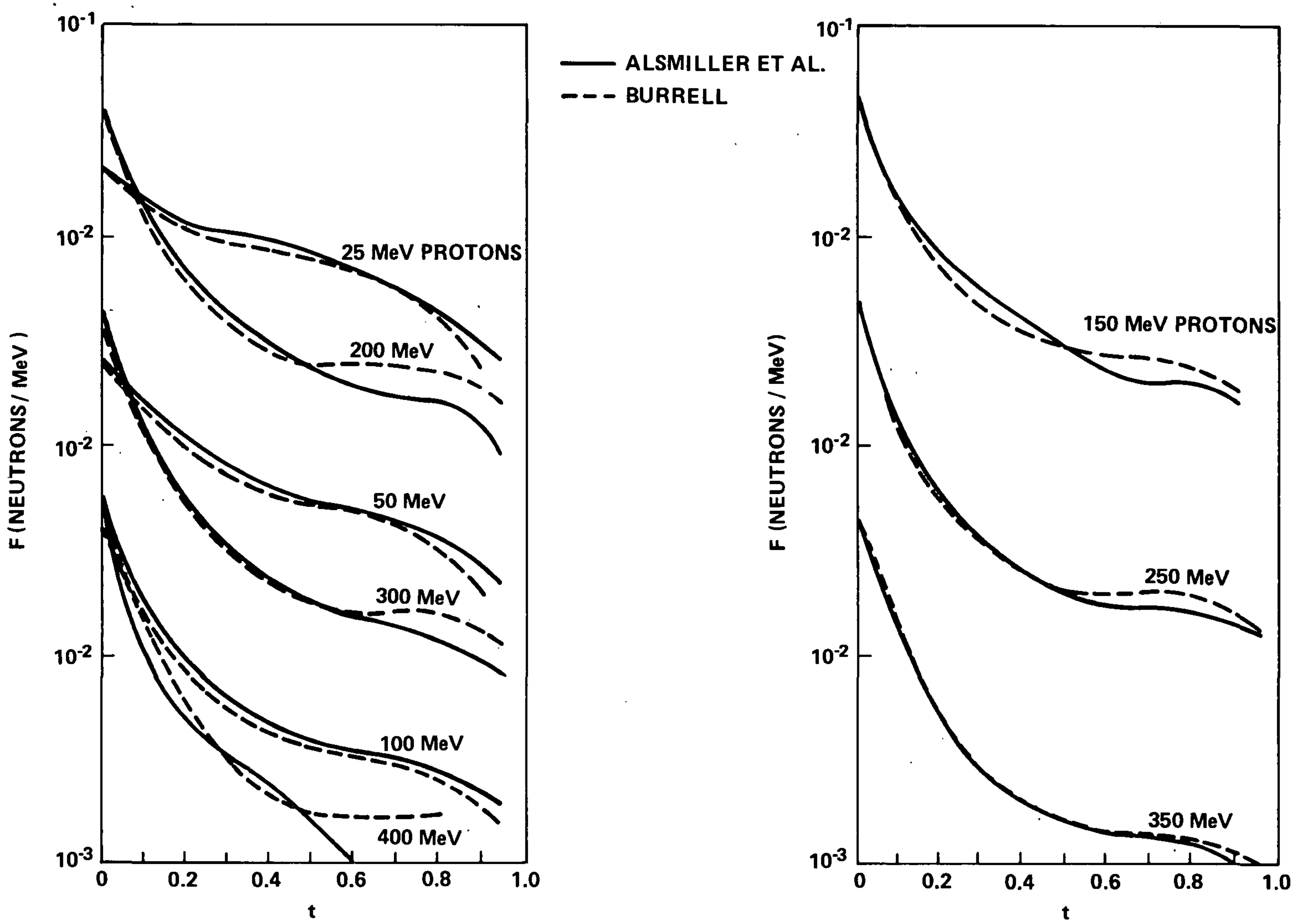

Figure 10. Cascade neutron spectra from uranium, A = 238, Z = 92.

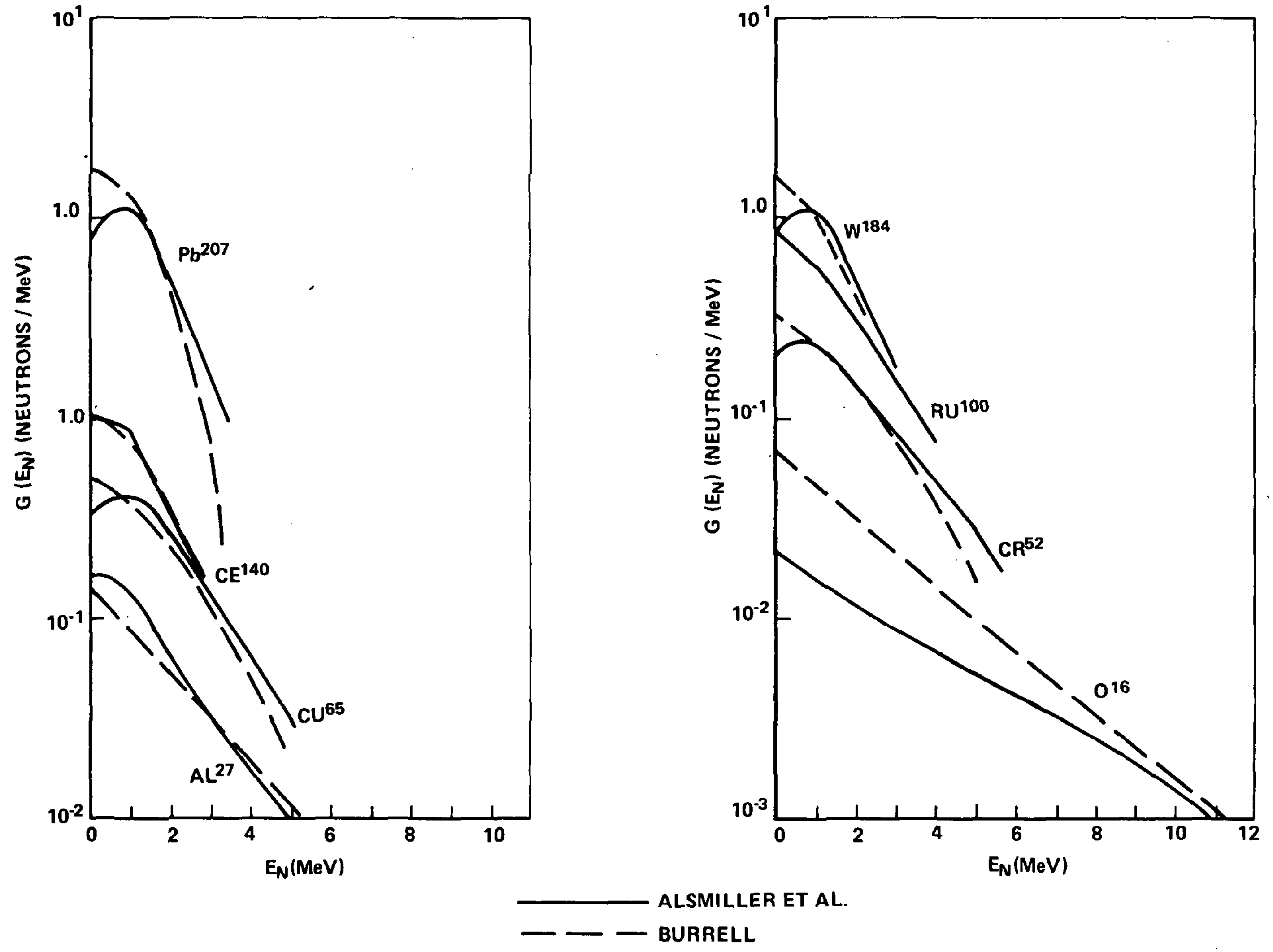

Figure 11. Evaporation neutron spectra for 25-MeV protons incident on nuclei.

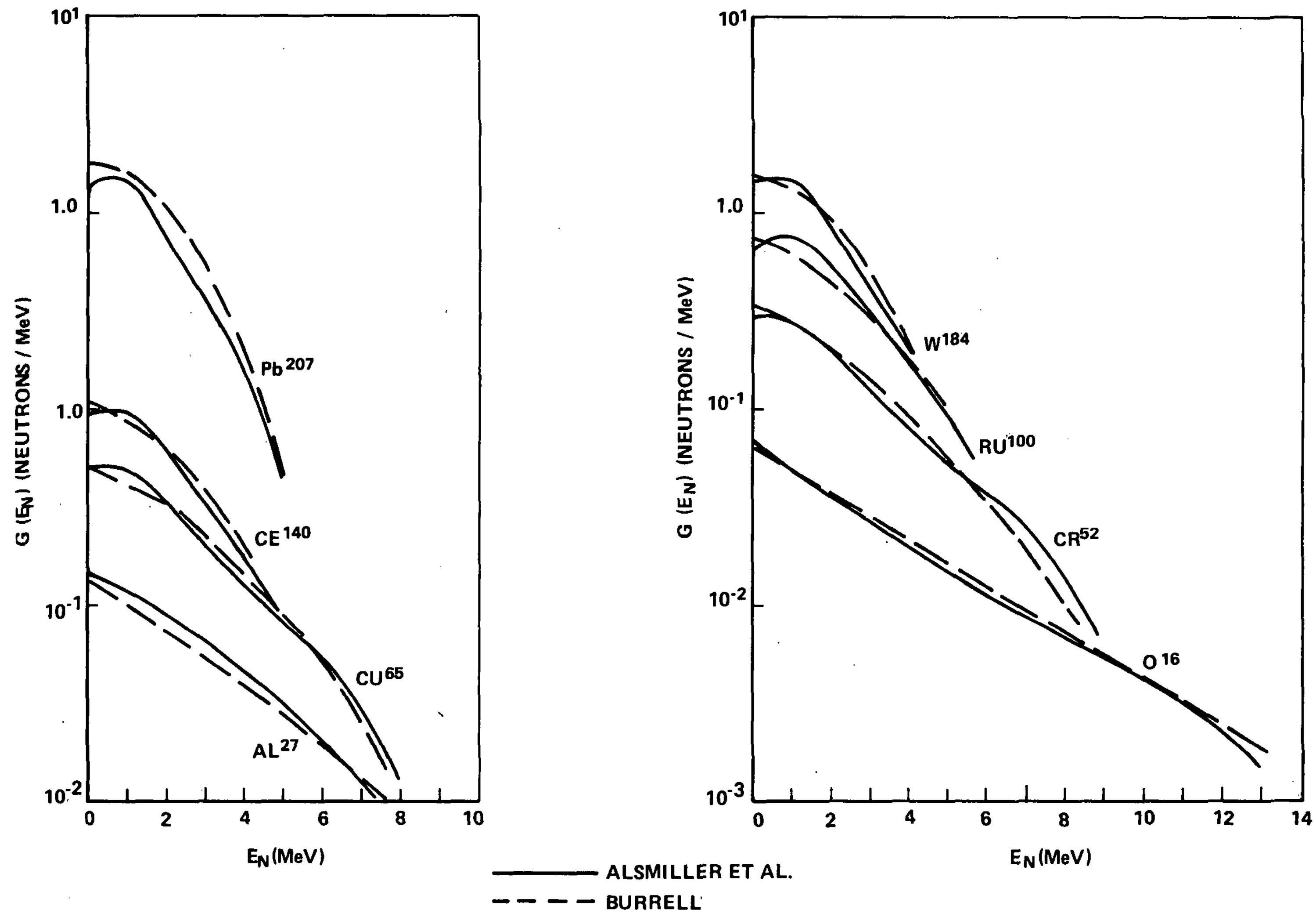

Figure 12. Evaporation neutron spectra from 50-MeV protons incident on nuclei.

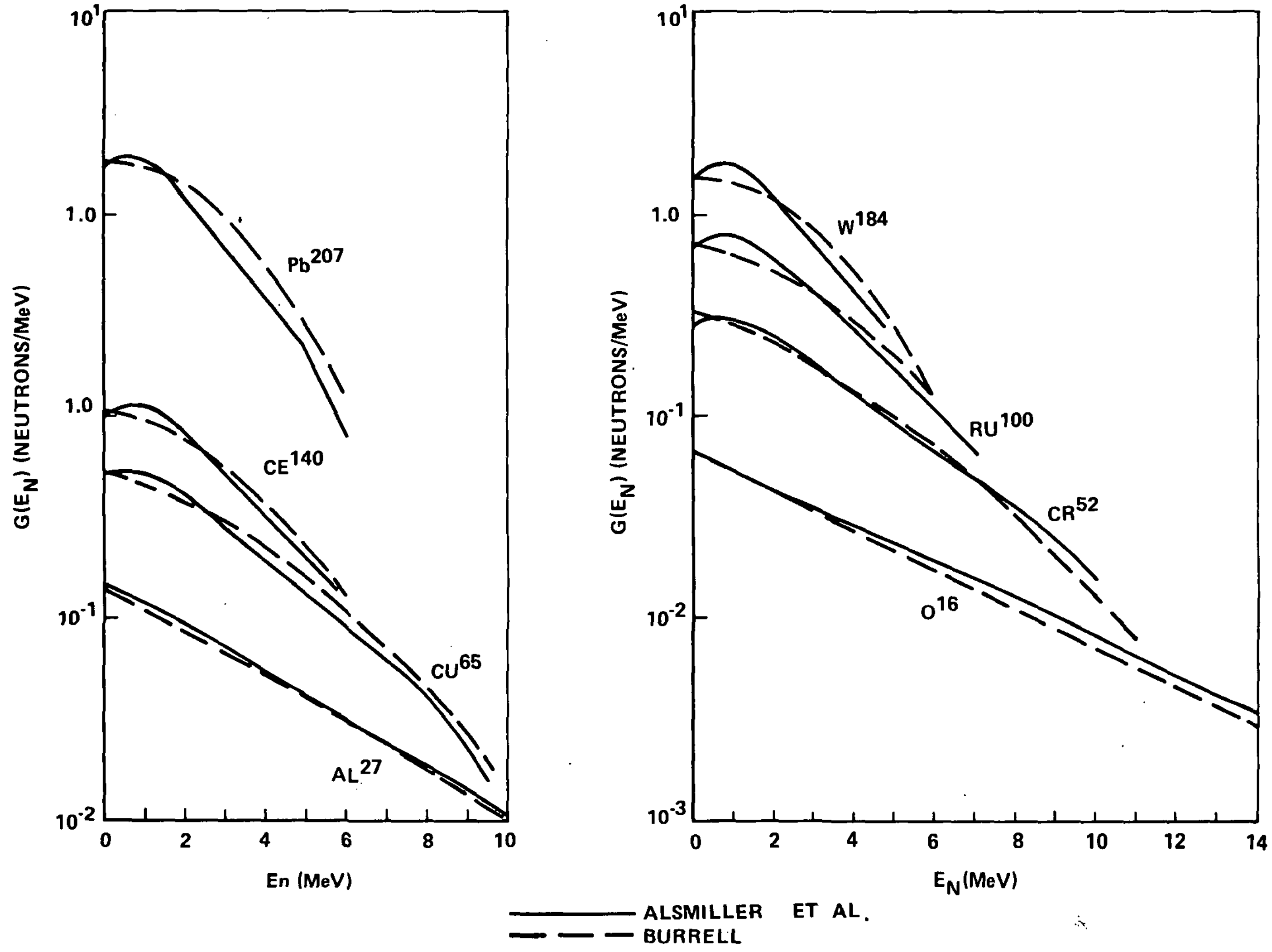

Figure 13. Evaporation neutron spectra from 100-MeV protons incident on nuclei.

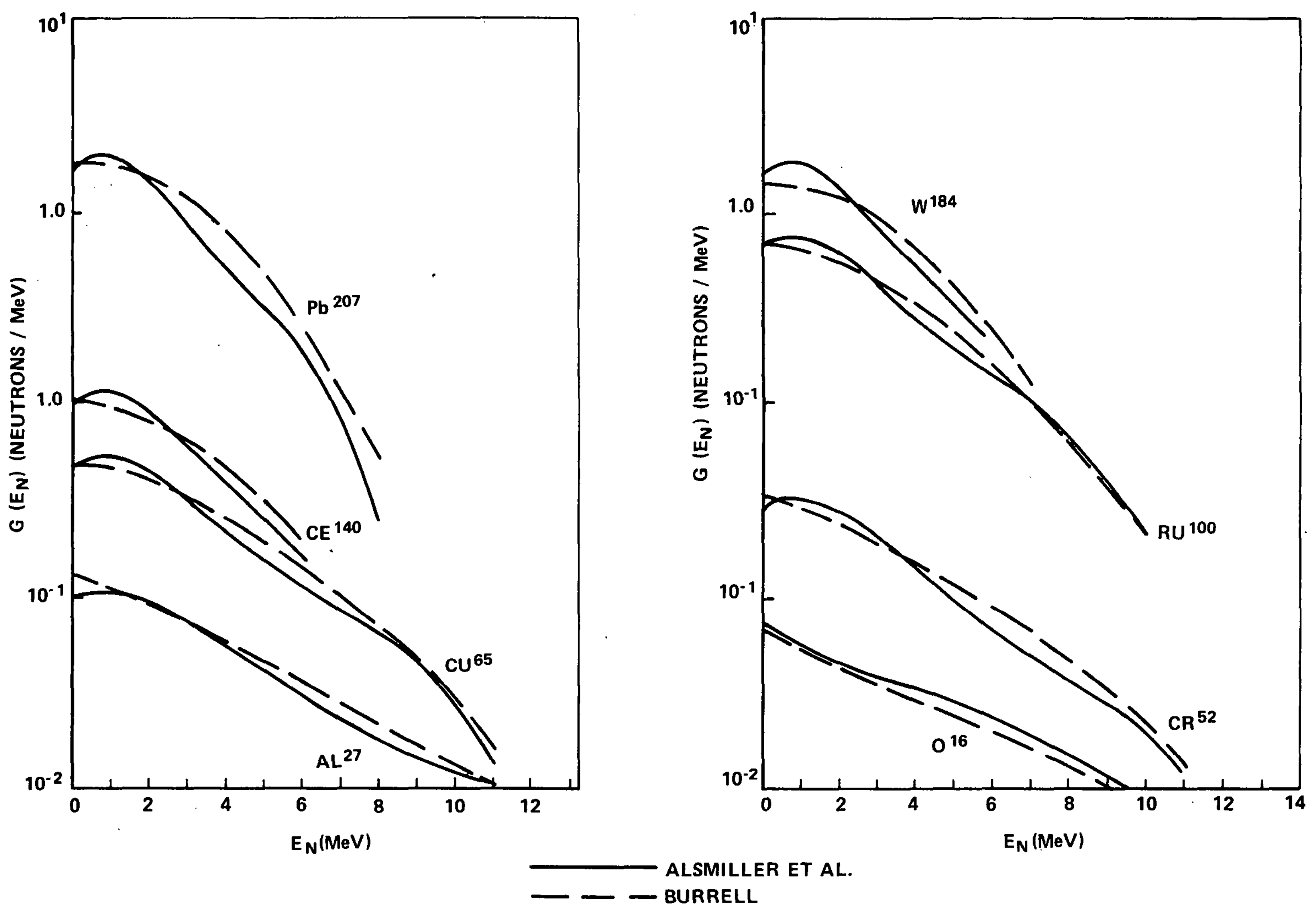

Figure 14. Evaporation neutron spectra for 150-MeV protons incident on nuclei.

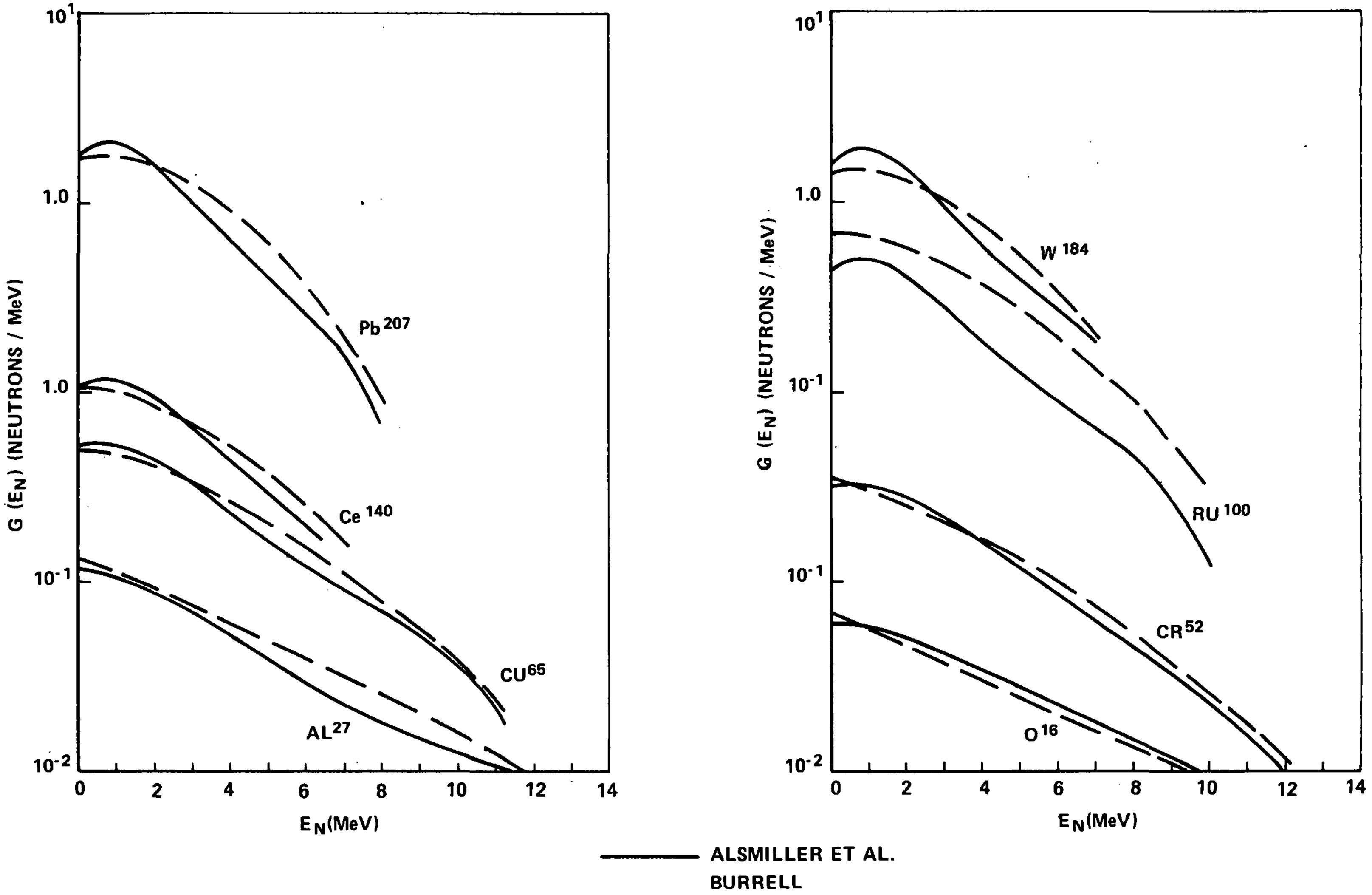

Figure 15. Evaporation neutron spectra for 200-MeV protons incident on nuclei.

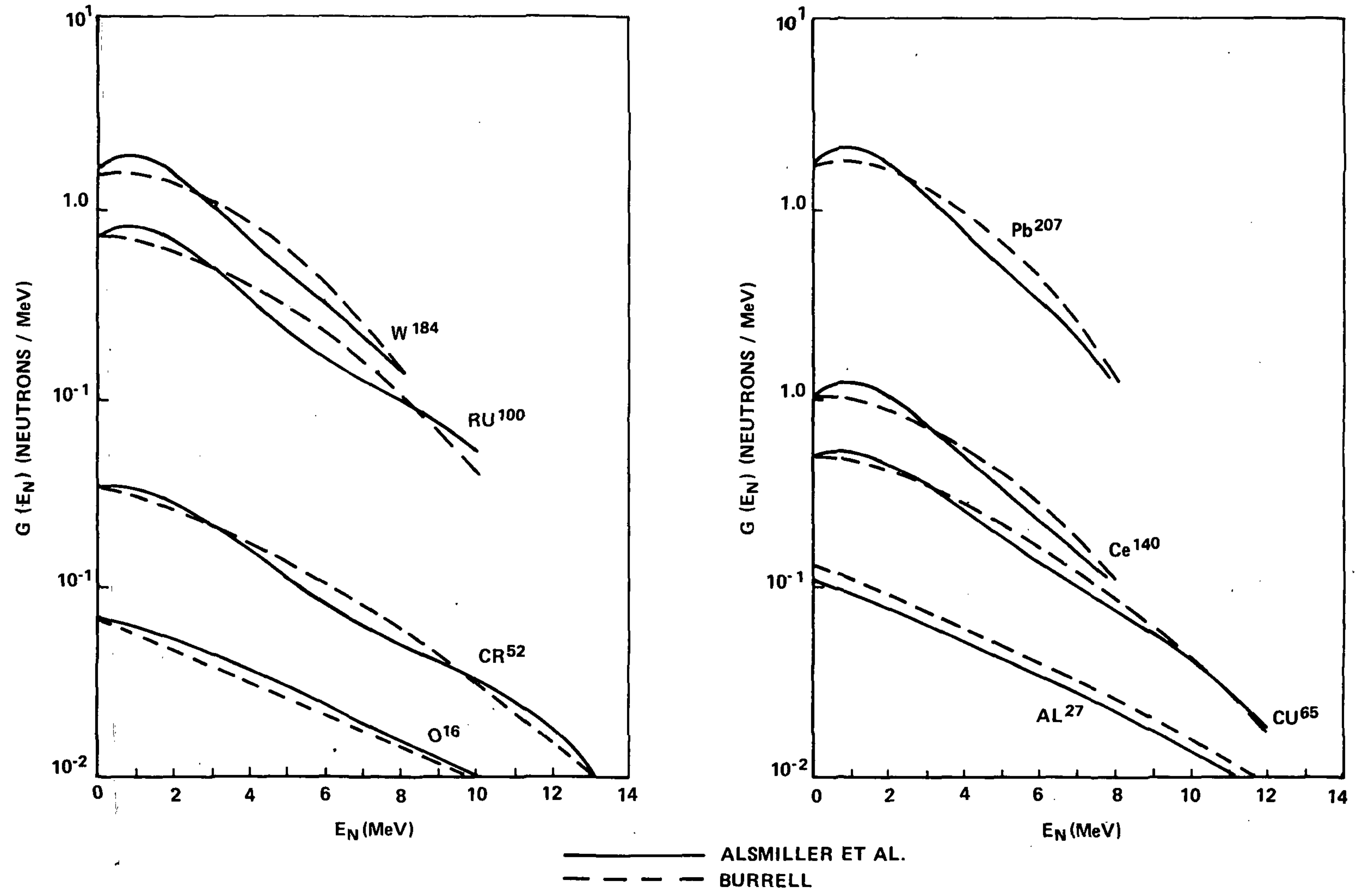

Figure 16. Evaporation neutron spectra for 250-MeV protons incident on nuclei.

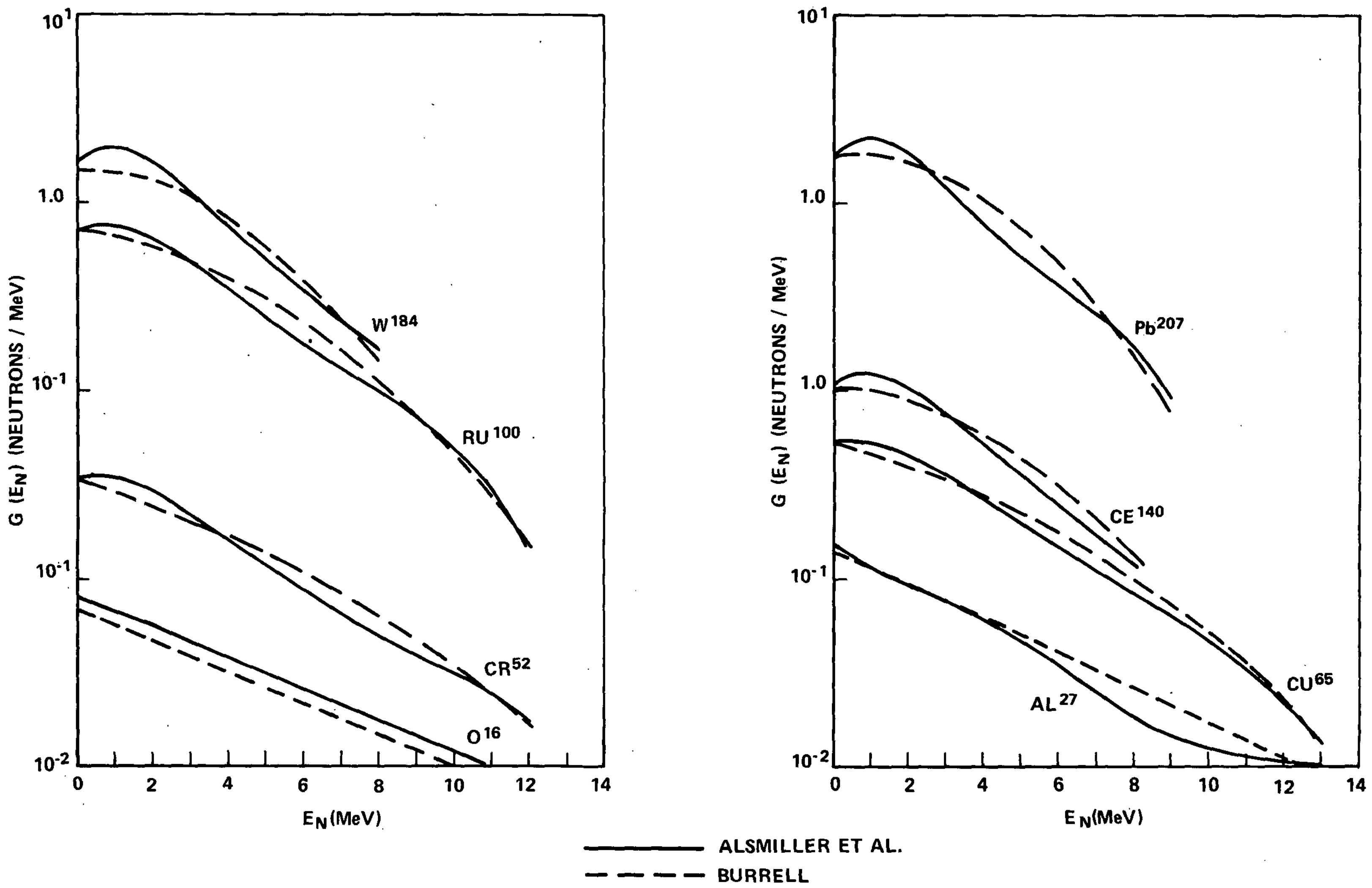

Figure 17. Evaporation neutron spectra for 300-MeV protons incident on nuclei.

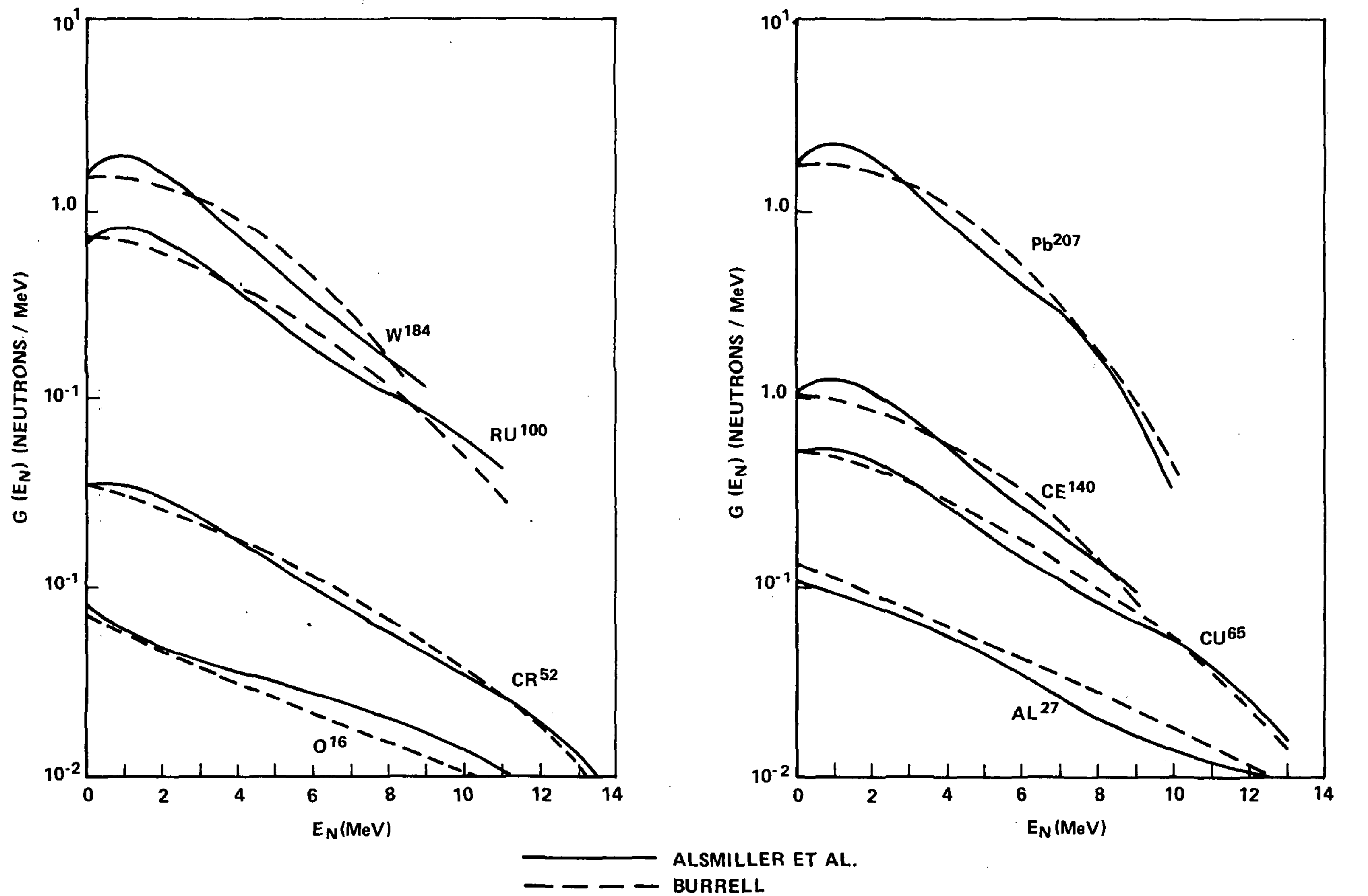

Figure 18. Evaporation neutron spectra for 350-MeV protons incident on nuclei.

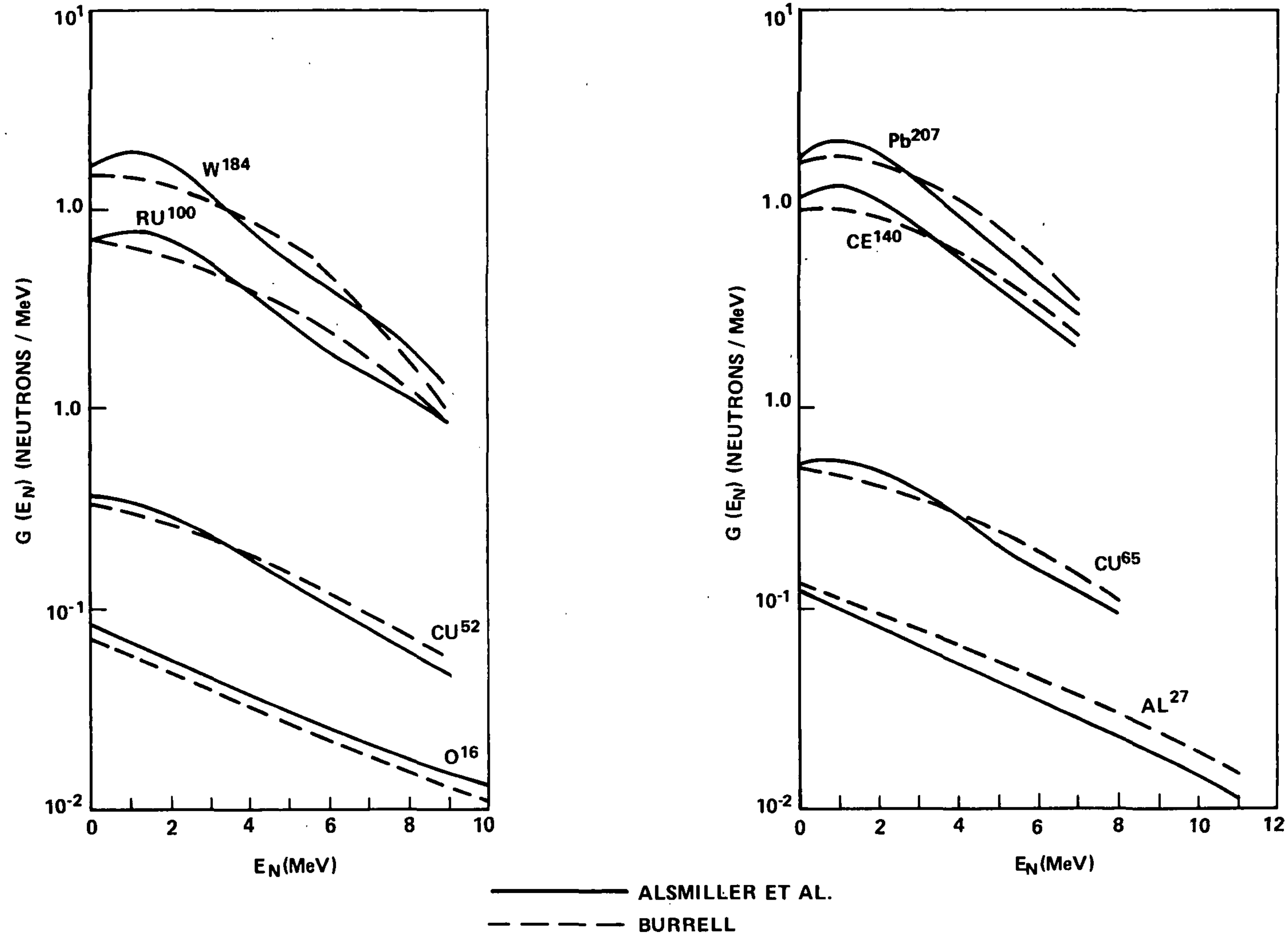

Figure 19. Evaporation neutron spectra for 400-MeV protons incident on nuclei.

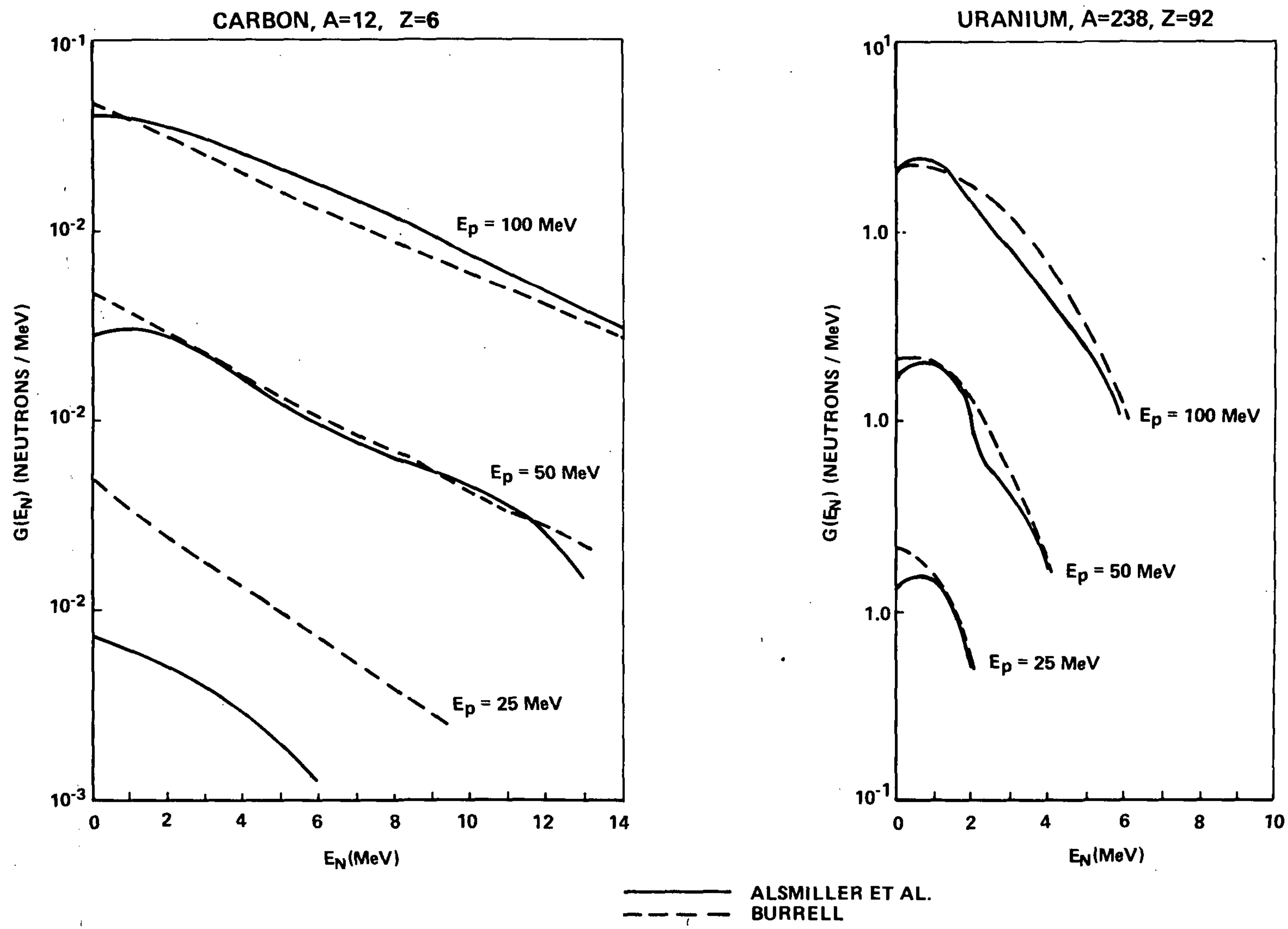

Figure 20. Evaporation neutron spectra from carbon A = 12, Z = 6, and uranium, A = 238, Z = 92.

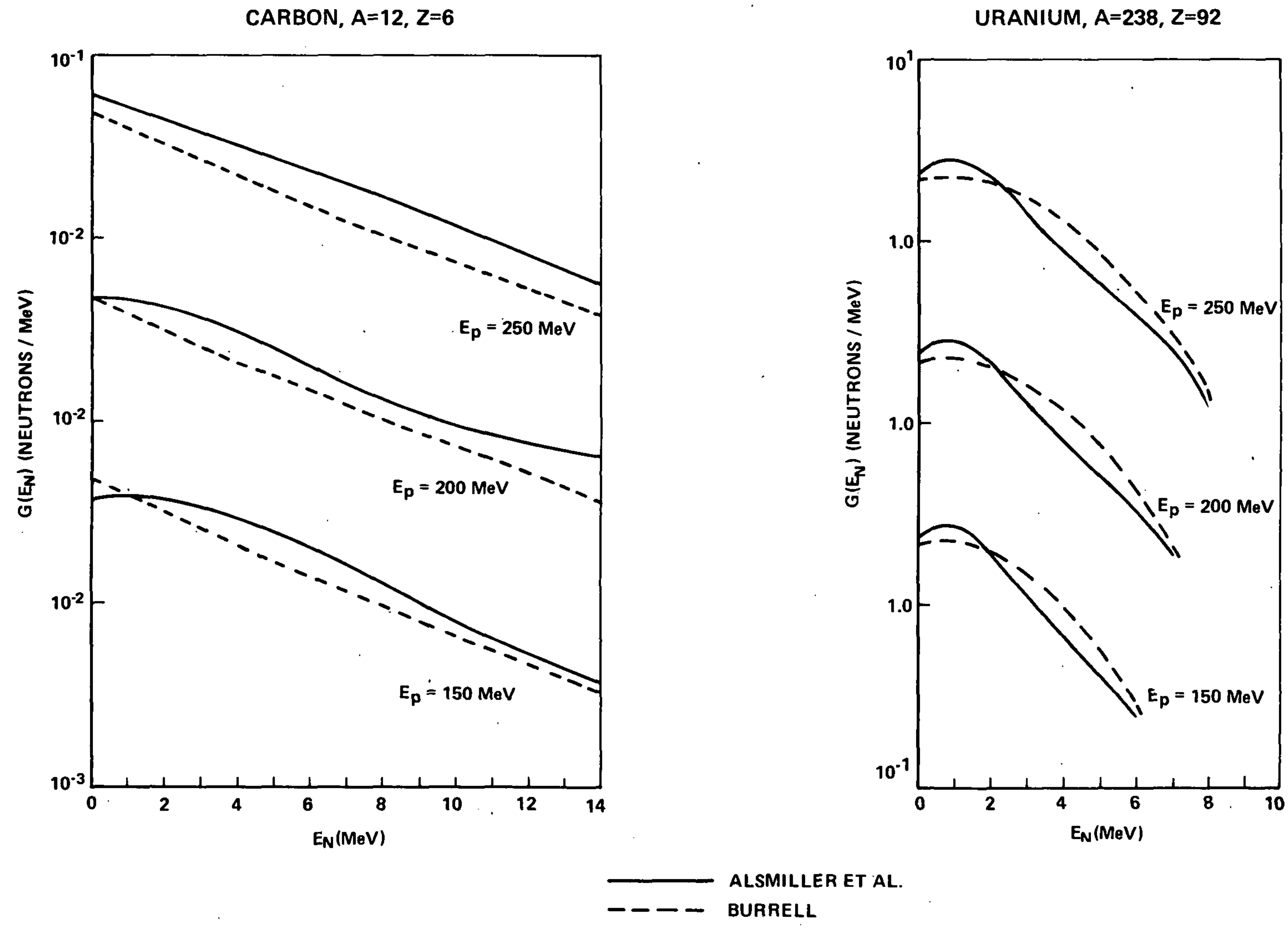

Figure 21. Evaporation neutron spectra from carbon, A = 12, Z = 6, and uranium, A = 238, Z = 92.

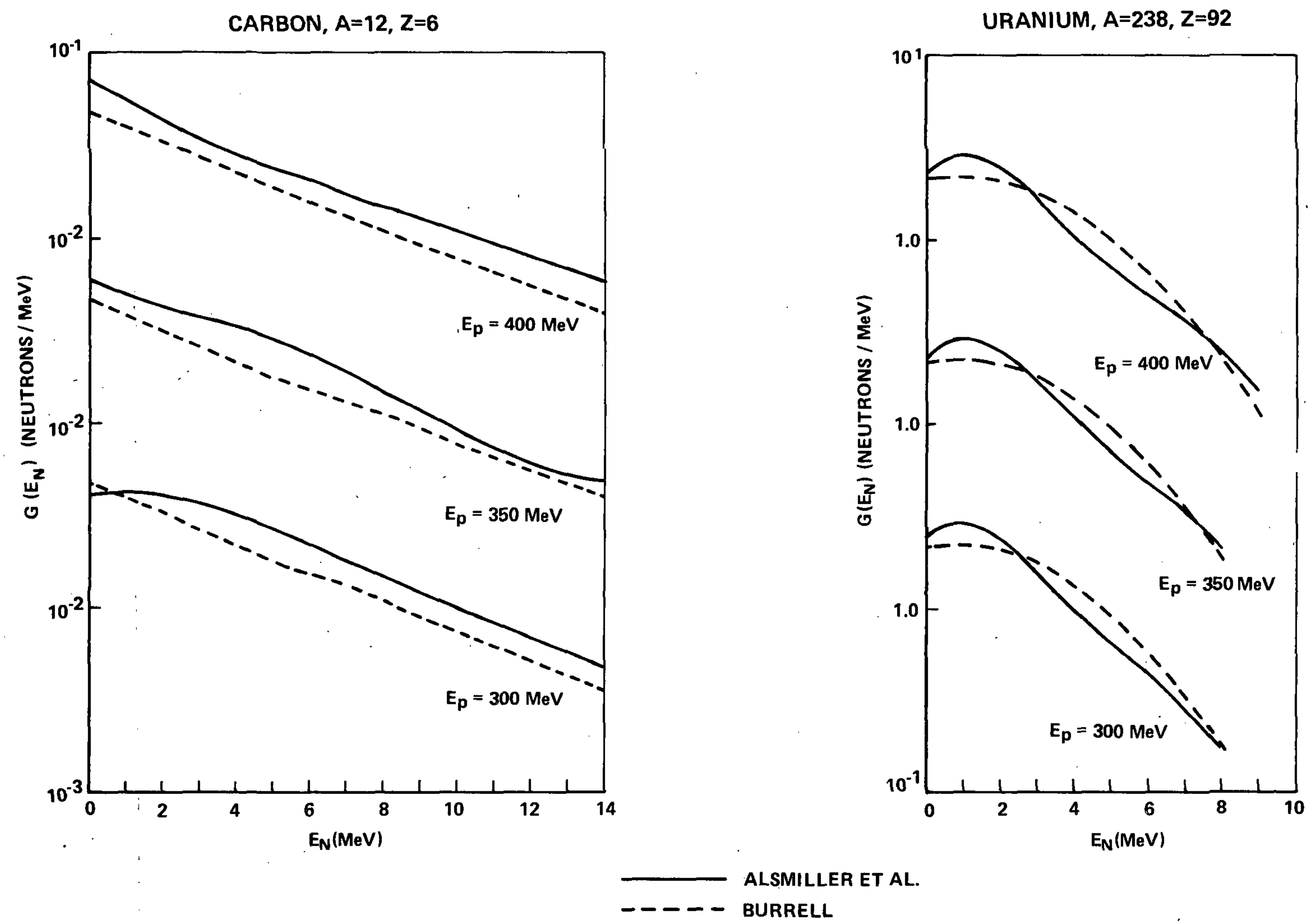

Figure 22. Evaporation neutron spectra from carbon, A = 12, Z = 6, and uranium, A = 238, Z = 92.

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